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QUARTERLY PROGRESS REPORT NO. 2
UNDER CONTRACT N00024-71-C-1266

1 July - 30 September 1971

NAVAL SHIP SYSTEMS COMMAND
Contract N00024-71-C-1266
Proj. Ser. No. SF 11552002, Task 8118

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ABSTRACT

In Section I a status report is given on the possible verification of ARL's forward scattering theory with data from the sea surface. The literature on forward and specular scattering has been thoroughly examined. No appropriate forward scatter data were found from the sea surface. Due to the lack of available sea surface data, a forward scatter experiment is presently being proposed at ARL's Lake Travis Test Station. A brief discussion and proposed experimental setup are described herein, along with some theoretical forward scatter predictions. In Section II the acoustic surface duct propagation problem for an irregular boundary is solved in terms of a contour integral. The roughness is incorporated into the boundary value problem by means of an effective reflection coefficient. Application is made to the surface duct transmission problem for a velocity-depth variation given by the Epstein profile.

TABLE OF CONTENTS

I. VERIFICATION OF THE ARL SCATTERING MODEL

The search in the literature for forward scattering data to be used to validate ARL's scattering model continued and was completed this quarter. The complete bibliography is given in the appendix of this report. The bibliography is not a complete listing of papers on scattering from the sea surface; theoretical papers and those concerned primarily with backscattering or reverberation were omitted. However, the list does represent a closed set of articles and reports on forward or specular scattering from rough surfaces. In other words, the reports are extensively cross-referenced within the bibliography itself, with few extraneous references to papers not included in the list.

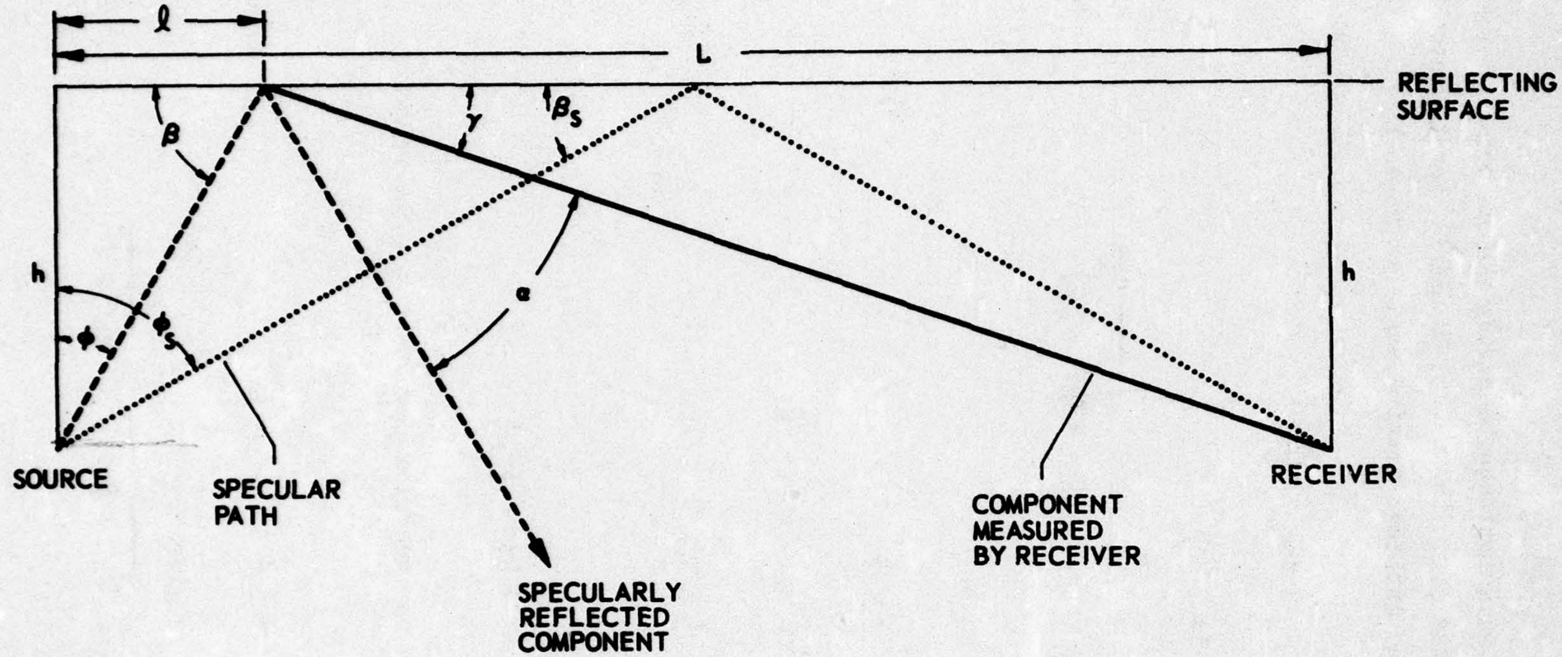
Very few of these reports were found to contain pertinent scattering data. The reports and papers that did present forward or specular scattering data were found to be unsuitable for comparison to ARL's theoretical predictions for several reasons. The most common reasons were that the data had been taken from model surfaces or that certain vital parameters (such as measurements of the surface statistics) were not included in the report. The model surface data in some cases were quite good but were rejected because the ARL scattering predictions have already been compared, with good results, to the scattering data taken from ARL's model surfaces.

In the absence of appropriate forward scatter data in the literature, an experiment has been designed and is being carried out to obtain forward scatter data at the Lake Travis Test Station of ARL.

Usual forward scatter experiments involve measuring the scattered field over a range of receiver angles with a fixed incident grazing angle. This series of measurements is then repeated for different incident angles. However, this type of experiment is difficult to carry out in an ocean or lake environment because of the changing receiver position and the large distances involved. More precise measurements of the incident and receiver angles and the related distances can be obtained when the scattered field from model surfaces is measured, where, for example, the receiver can be placed on a rotating boom, as in the ARL scattering experiments. The difficulty of measuring these angles and distances and of obtaining accurate measurements of the surface statistical parameters are two of the prime factors limiting the amount of forward scatter data that has been taken at sea.

The Lake Travis experiment has been designed so that the receiver position remains fixed throughout a single data run. The source position must also remain fixed, but the source will be rotated to change the incident grazing angle. Thus, it is only necessary to know the depth of the source and receiver, the tilt angles of the source, and the source-receiver separation to make a single data run. Rotating the source will change the direction of the specularly reflected component, and, hence, the receiver will assume several different angles with respect to the specular direction in the course of a single run. The geometry of this experiment is shown in Dwg. AS-71-1095.

In order to convert the theoretical formulas in the ARL model to this particular geometry, it will be necessary to find the new relation between the incident grazing angle, β, and the receiver angle, γ. Also the changing pathlengths must be correctly accounted for (the total pathlength, as well as the source and receiver distances, were previously assumed constant for any combination of incident and



SCATTERING GEOMETRY

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receiver angles). These relations can be easily worked out in terms of the distances and angles given in Dwg. AS-71-1095. For the case of specular reflection the incident grazing angle is given by

$$\beta_s = \tan^{-1}\left(\frac{2h}{L}\right) \quad ,$$

and the total pathlength is

$$\text{pathlength (specular)} = 2\sqrt{h^2 + \left(\frac{4}{2}\right)^2} \quad . \tag{1}$$

For the nonspecular case,

$$\beta = \frac{\pi}{2} - \Phi \quad , \tag{2}$$

where Φ is the known source tilt angle, so

$$\ell = \frac{h}{\tan \beta} \quad ,$$

and

$$\gamma = \tan^{-1}\left(\frac{h}{L-\ell}\right) \quad . \tag{3}$$

Finally the angle between the specular component and the received component is given by

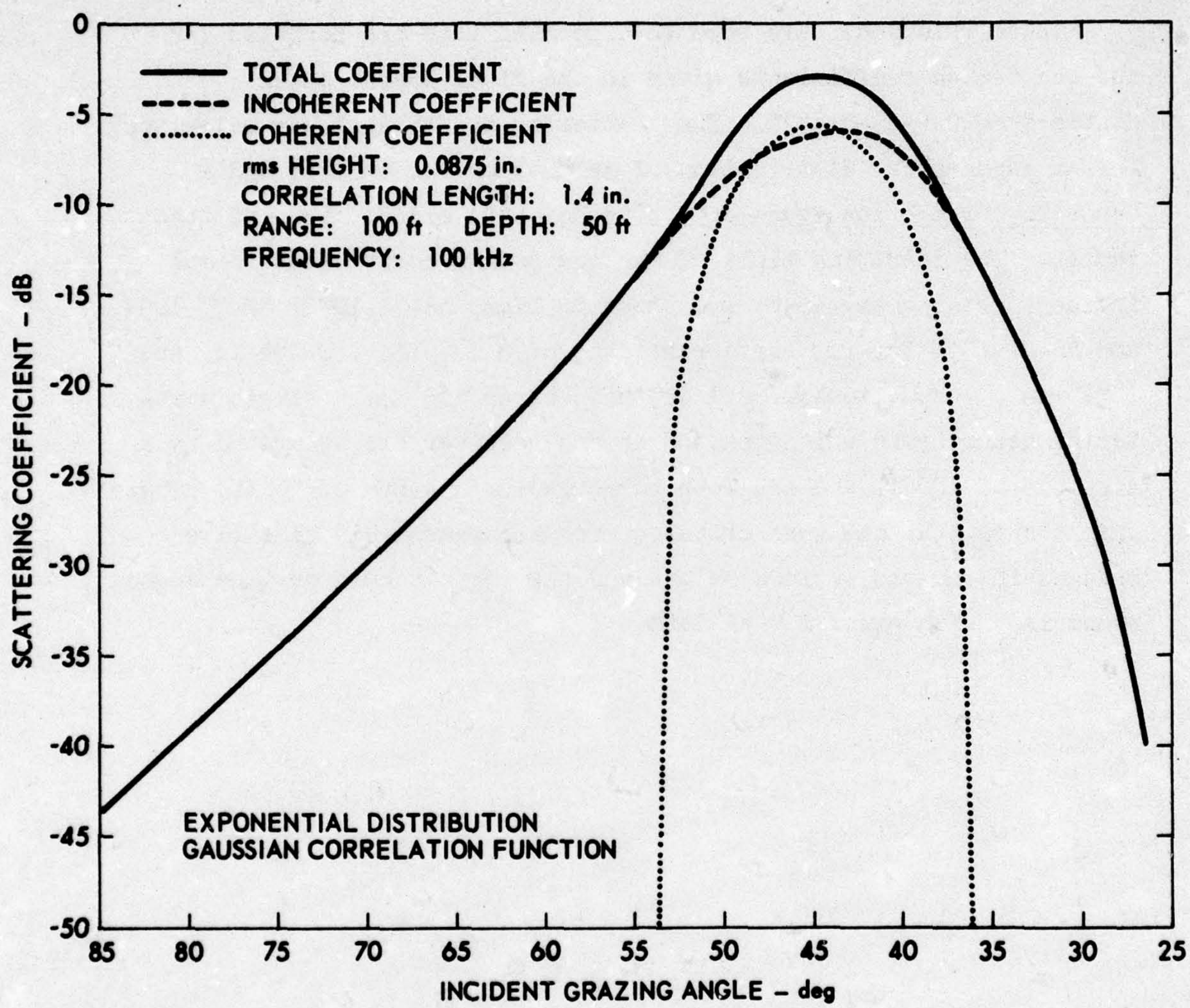
$$\alpha = \beta - \gamma \quad , \tag{4}$$

and the total pathlength is given by

$$\text{pathlength} = \sqrt{h^2 + (L-\ell)^2} + \sqrt{h^2 + \ell^2} \quad , \tag{5}$$

where the first term represents the distance from the receiver to the point of reflection on the surface, and the second term is the distance from that point to the source.

These relations have been incorporated into the formulas for the scattering coefficients given in the Final Report under Contract N00024-69-C-1275. The scattering coefficient was calculated for an exponential distribution of heights on the surface and a Gaussian correlation function, using Eq. (75) and Eq. (79) of that report. The resulting plots of the scattering coefficient versus incident grazing angle, β, are shown in Dwgs. AS-71-1096, AS-71-1097, and AS-71-1098 for rms surface heights of 0.0875 in., 0.284 in. and 0.875 in., respectively. All of these plots are for a single scattering geometry in which the source and receiver are separated by a distance of 100 ft and are both submerged at a depth of 50 ft. These graphs show that the theoretical curves are reasonably sensitive to changes in the rms surface height and therefore should provide a good comparison with experimental data.



SCATTERING COEFFICIENT vs INCIDENT GRAZING ANGLE

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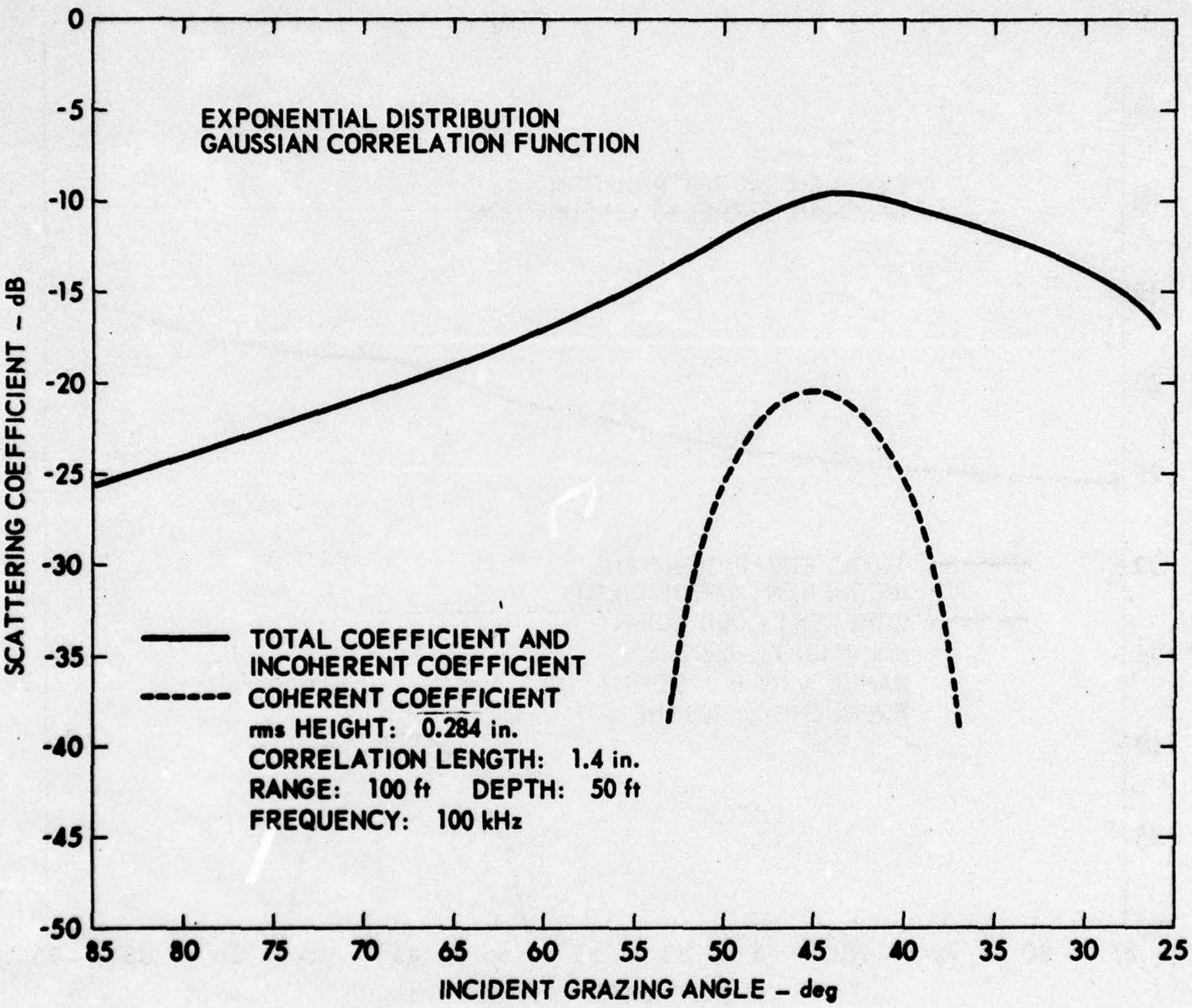

SCATTERING COEFFICIENT vs INCIDENT GRAZING ANGLE

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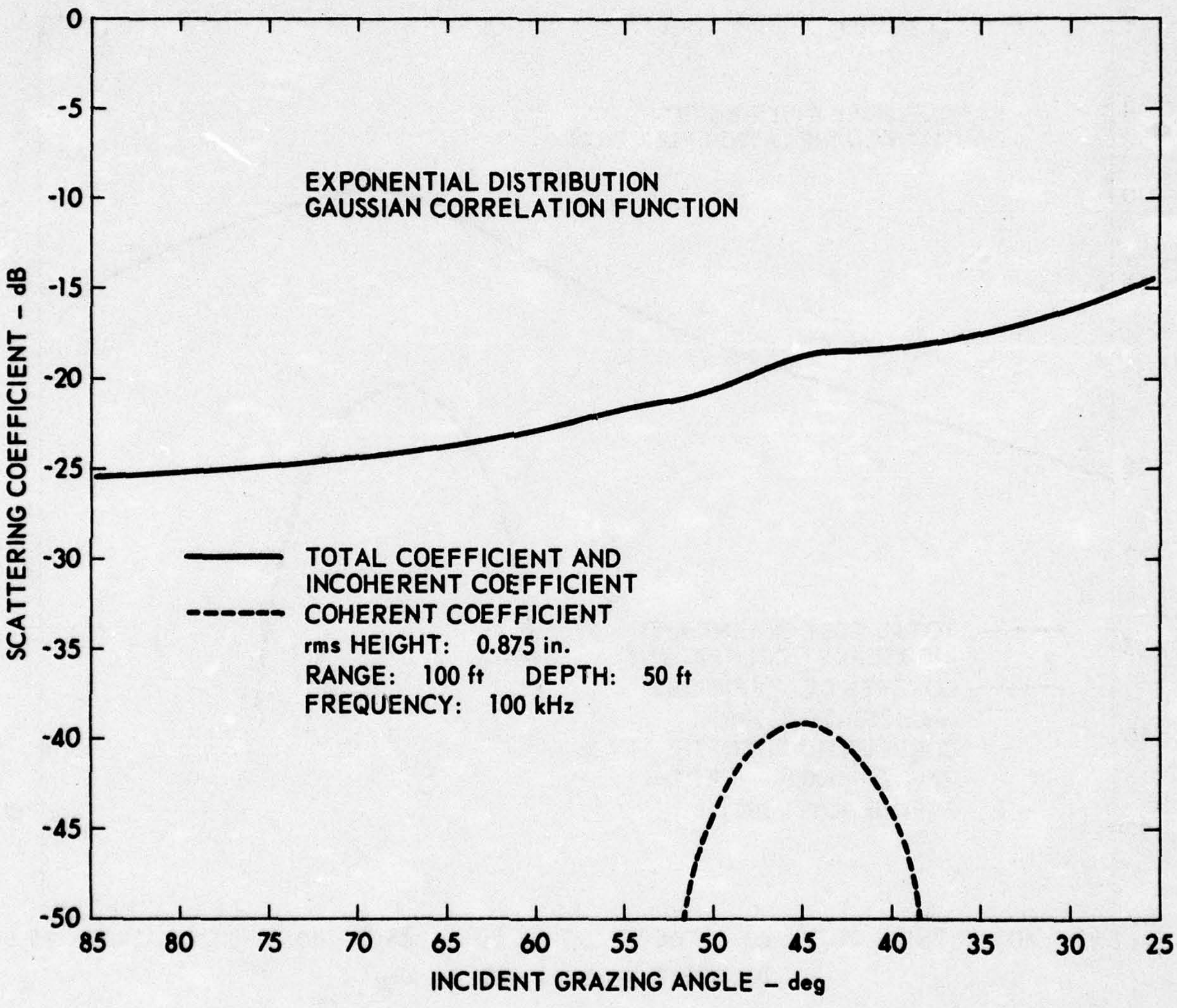

SCATTERING COEFFICIENT vs INCIDENT GRAZING ANGLE

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II. SOUND PROPAGATION IN A SURFACE DUCT WITH A ROUGH BOUNDARY

The purpose of this section is to show how existing contour integral solutions can be used in solving the surface duct propagation problem when the surface is irregular. This method is different from that used previously by Bucker.[1,2]

The acoustic field is derived for a cw point source located in an inhomogeneous medium with a rough surface. Application is made to a class of surface duct profiles in which the velocity-depth variation is almost isovelocity near the surface (as shown in Dwg. AS-71-1099). The bilinear and Epstein profiles fit this class of velocity variations very well.

A. Green's Function Solution

The wave equation for a point source with angular frequency ω located in a layered inhomogeneous medium is given by

$$\nabla^2 P - \frac{1}{C^2(Z)} \frac{\partial^2 P}{\partial^2 t} = -4\pi Q_o \delta(\bar{r}-\bar{r}_o)\, e^{-i\omega t} \quad , \tag{6}$$

where P represents the pressure, $C(Z)$ is the sound velocity (variable in the depth coordinate Z), and $\delta(\bar{r}-\bar{r}_o)$ is the three-dimensional Dirac delta function. The strength of the source is designated by Q_o. If cylindrical coordinates (r,θ,Z) are assumed to have azimuthal

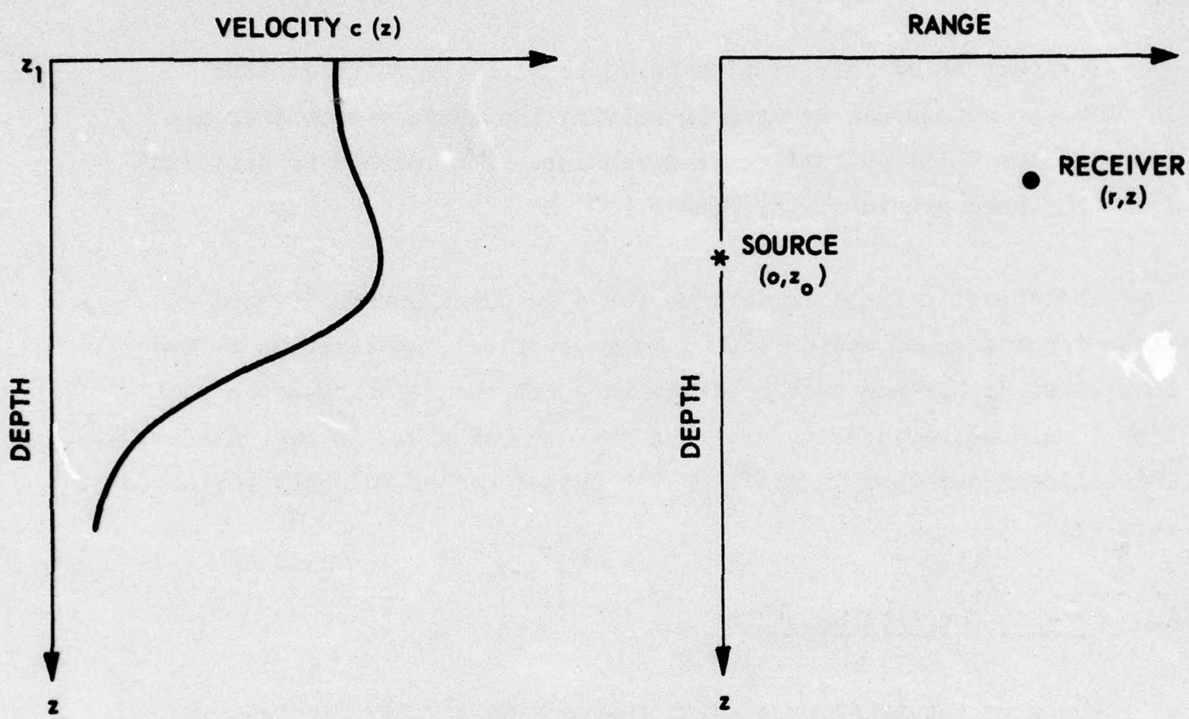

DIAGRAM OF WAVEGUIDE SHOWING LOCATION
OF SOURCE AND RECEIVER

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symmetry and a time factor of $\exp(-i\omega t)$ is suppressed, the following equation is obtained:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P}{\partial r}\right) + \frac{\partial^2 P}{\partial Z^2} + k^2(Z)P = \frac{-2Q_o\delta(r)\delta(Z-Z_o)}{r} \quad , \tag{7}$$

where P now represents the time independent pressure. The wave number $k(Z)$ is defined as $\omega/C(Z)$ and the source is located at $Z = Z_o$ and $r = 0$, as indicated in Dwg. AS-71-1099. The vertical depth coordinate Z varies from $Z_1 \leq Z \leq \infty$, and the range coordinate r varies from $0 < r < \infty$. Boundary conditions imposed on Eq. (7) are that

(a) P must satisfy a radiation condition for $r \rightarrow \infty$,

(b) effective upgoing and downgoing reflection coefficients are specified at the surface $Z = Z_1$,

(c) P and $\frac{\partial P}{\partial Z}$ be continuous across any discontinuities in the velocity-depth profile.

The statistical nature of the surface is introduced through one of the effective reflection coefficients.

In the Green's function approach, Eq. (7) is separated into the following forms:

$$\left[\frac{d}{dr}\left(r\frac{d}{dr}\right) + \lambda_1 r\right] G_1(r,\lambda_1) = -2\delta(r) \quad , \tag{8}$$

$$\left[\frac{d^2}{dZ^2} + k^2(Z) - \lambda_1\right] G_2(Z,Z_o,-\lambda_1) = -Q_o\delta(Z-Z_o) \quad , \tag{9}$$

where λ_1 is the separation constant. By the resolvent Green's function technique, the solution of Eq. (7) is given by a complex convolution of G_1 and G_2,

$$P(r,Z,Z_o) = \frac{1}{2\pi i} \int_C G_1(r,\lambda_1)\, G_2(Z,Z_o,-\lambda_1)d\lambda_1 \quad , \qquad (10)$$

where the contour C separates the singularities of the Green's functions.

The solution of Eq. (8) which satisfies the required boundary conditions is given by

$$G_1(r,\lambda_1) = i\pi H_o^1(\xi r) \qquad \left(\xi = \lambda_1^{1/2},\ 0 < \arg \lambda_1 < 2\pi\right) \quad , \qquad (11)$$

where $H_o^1(k_o rs)$ is the Hankel function of the first kind, and where

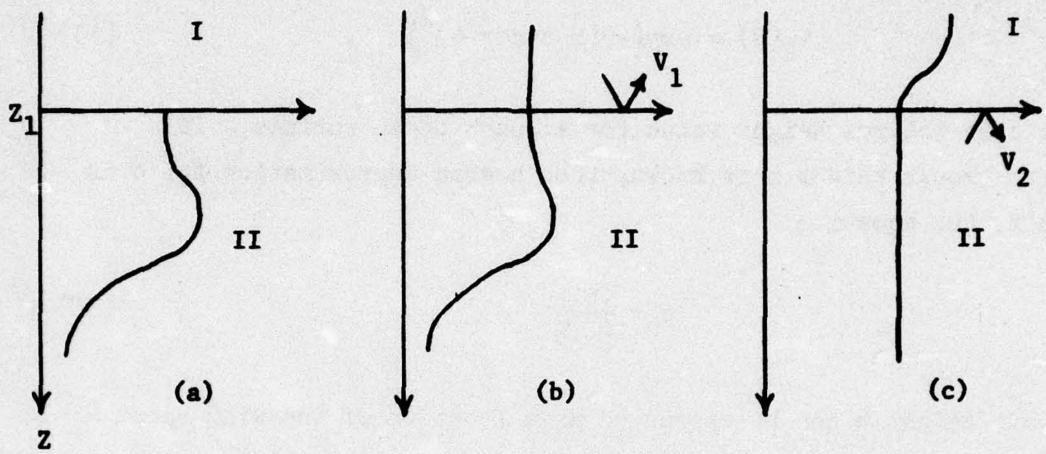
$$\xi \equiv k_o \sin\theta \equiv k_o s \quad , \qquad (12)$$

θ is the angle of incidence, and k_o is the wave number at the surface $Z = Z_1$. The solution of Eq. (9) that satisfies the required boundary conditions is given by

$$G(Z,Z_o,s) = \frac{-i}{2k_o(1-s^2)^{1/2}} \frac{f_2(Z_o)f_1(Z)}{1 - V_1V_2} \quad Z_1 < Z < Z_o$$

$$G(Z,Z_o,s) = \frac{-i}{2k_o(1-s^2)^{1/2}} \frac{f_2(Z)f_1(Z)}{1 - V_1V_2} \quad Z_o < Z < \infty \quad . \qquad (13)$$

In order to define the functions in Eq. (13), Dwg. AS-71-1099 is separated as shown in the following sketch.



The idea is to divide an inhomogeneous layer into two profiles where each has a homogeneous half-space. In the present application, region I of sketch (c) is also homogeneous. $V_1(\theta)$ is defined as the reflection coefficient of a plane wave incident from the homogeneous medium onto the lower inhomogeneous half-space [sketch (b)]. The function $f_1(Z)$ is the field in the inhomogeneous half-space II - b, when the incident wave has unit amplitude. $V_2(\theta)$ and $f_2(Z)$ have an analogous meaning in sketch (c). At the source $f_1(Z_o) = 1+V_1$ and $f_2(Z_o) = 1+V_2$.

When Eq. (11) and Eq. (13) are used in Eq. (10), the solution for Eq. (7) is obtained,

$$P(r,Z,Z_o) = \frac{-ik_oQ_o}{2} \int_C \frac{f_2(Z_o)f_1(Z)}{1 - V_1V_2} H_o^1(k_o rs) \frac{sds}{c} \quad Z_1 < Z < Z_o \quad ,$$

$$P(r,Z,Z_o) = \frac{-ik_oQ_o}{2} \int_C \frac{f_2(Z)f_1(Z_o)}{1 - V_1V_2} H_o^1(k_o rs) \frac{sds}{c} \quad Z_o < Z < \infty \quad , \tag{14}$$

where $s \equiv \sin\theta$ and $c \equiv \cos\theta$.

For the case where Z_1 is a lossy boundary, then, from classical scattering theory the form for V_2 can be given as

$$V_2(\theta) = \exp\left(-2(k_o \sigma \cos \theta)^2\right) \quad , \tag{15}$$

where σ is the rms height value for a rough ocean surface. If a peak to trough height h is known, then a good approximation for σ is given by the equation

$$\sigma = \frac{h}{2\sqrt{2}} \quad . \tag{16}$$

The wave height h can be expressed as a function of the wind speed W (in knots) by the following relation (derived by Schulkin):

$$h = 0.00276\ W^{5/2} \quad , \tag{17}$$

where h is given in feet.

Equation (14) will now be applied to the case of a rough surface bounding an Epstein profile. This profile is used instead of the bilinear because it does not have any velocity-depth discontinuities.

B. Epstein Profile with a Rough Surface

The Epstein profile is a four-parameter velocity function which has had many applications. Since Eckart as well as Rosen and Morse examined this function about the same time that Epstein did,it is sometimes known by other names. Specifically, the velocity-depth profile known as the Epstein function is given by

$$\frac{1}{C^2(Z)} = A \operatorname{sech}^2 \frac{Z}{H} + B \tanh \frac{Z}{H} + D \quad , \tag{18}$$

where the quantities A, B, D, and H are profile parameters. Bucker and Morris[3] have given a normal mode treatment for an Epstein surface duct with a pressure release boundary. The profile shown in Dwg. AS-71-1100 has been taken, with permission, from the paper by Bucker and Morris.

Epstein chose this function because it allows Eq. (9) to be solved in terms of hypergeometric functions. Specifically, the traveling-waves solutions to the homogeneous Eq. (9) are given by[4]

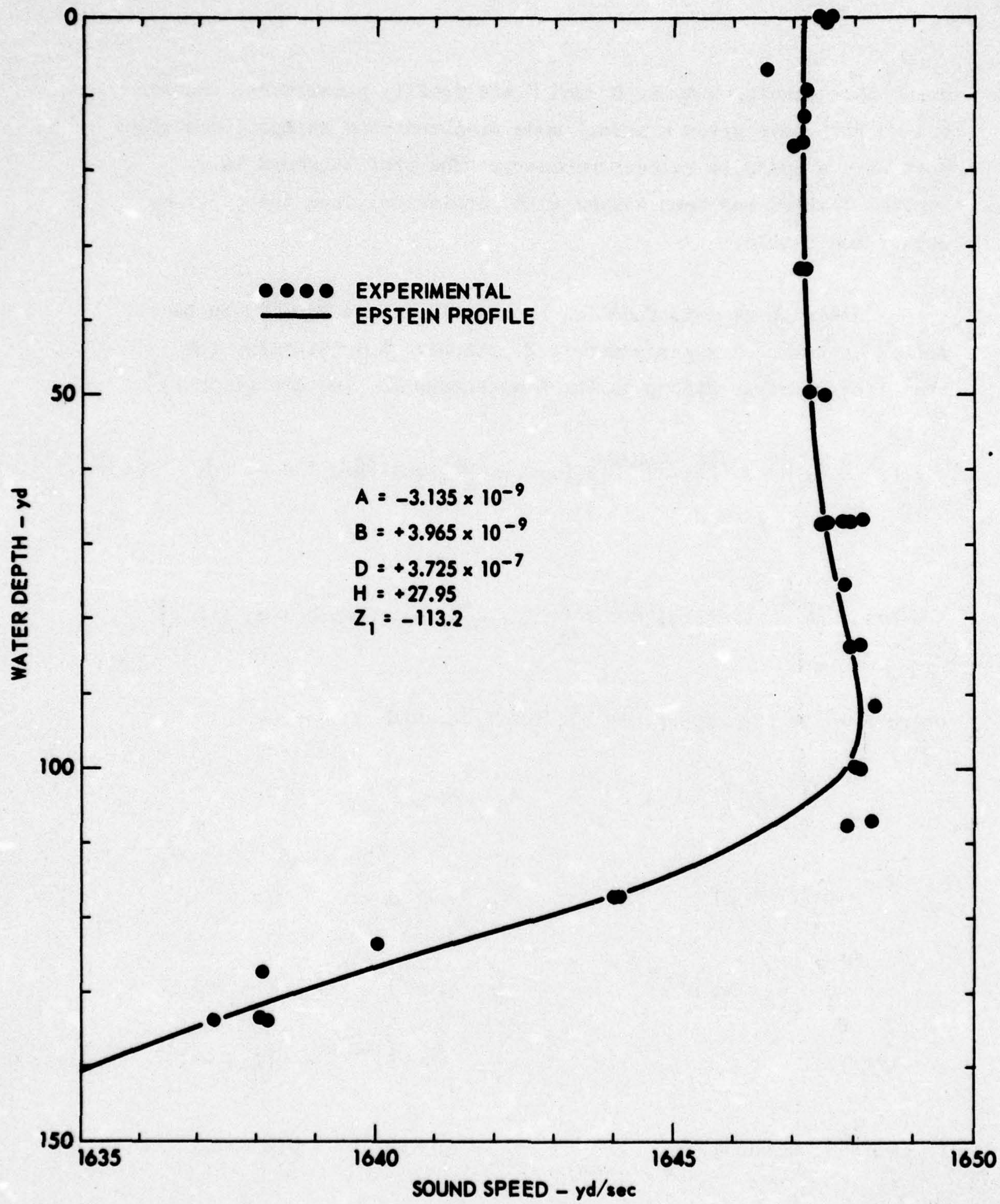
$$n_1(Z) = \left(\frac{H}{2}\right)^{1/2} x^{\lambda/2}(1-x)^{\mu/2}\ F_1\left(1-\nu + \frac{\lambda+\mu}{2},\ \nu + \frac{\lambda+\mu}{2};\ 1 + \lambda;\ x\right) \tag{19}$$

and

$$n_2(Z) = \left(\frac{H}{2}\right)^{1/2} x^{\lambda/2}(1-x)^{\mu/2}\ F_2\left(1-\nu + \frac{\lambda+\mu}{2},\ \nu + \frac{\lambda+\mu}{2};\ 1 + \mu;\ 1 - x\right) \quad , \tag{20}$$

where F(x) is the hypergeometric function, and

$$\begin{aligned}
\mu &= H\left(\zeta^2 - k_\infty^2\right)^{1/2} \quad , & k_\infty &= \omega/C_\infty \quad , \\
\lambda &= H\left(\zeta^2 - k_{-\infty}^2\right)^{1/2} \quad , & k_{-\infty} &= \omega/C_{-\infty} \quad , \\
\nu &= \frac{1}{2} + \left(\frac{1}{4}\ A\omega^2 H^2\right)^{1/2} \quad , & C_\infty &= (D+B)^{-1/2} = C(Z = +\infty) \quad , \\
\zeta &= Z/H \quad , & C_{-\infty} &= (D-B)^{-1/2} = C(Z = -\infty) \quad , \\
x &= (1+\tanh \zeta)/2 \quad , & C_0 &= (D+A)^{-1/2} = C(Z = 0) \quad .
\end{aligned} \tag{21}$$



EPSTEIN SURFACE DUCT VELOCITY
DEPTH PROFILE

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The following limiting forms are

$$\lim_{Z \to -\infty} n_1(Z) \sim (H/2)^{1/2} \exp(\lambda\zeta)$$
$$(22)$$
$$\lim_{Z \to +\infty} n_2(Z) \sim (H/2)^{1/2} \exp(-\mu\zeta) \quad .$$

Also when $k_{\infty}^2 > \xi^2$ and $k_{-\infty}^2 > \xi^2$, then

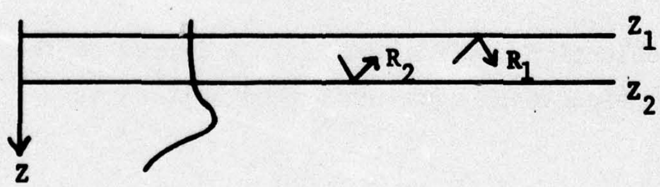
$$\left(\xi^2 - k_{-\infty}^2\right)^{1/2} = -i\left(k_{-\infty}^2 - \xi^2\right)^{1/2}$$

and (23)

$$\left(\xi^2 - k_{\infty}^2\right)^{1/2} = -i\left(k_{\infty}^2 - \xi^2\right)^{1/2} \quad .$$

In order to find the pressure field in an Epstein surface duct, the appropriate Green's function must be specified. Equation (13) will now be given in a more general form.

The following diagram is necessary for the definition of the Green's function.



When $Z_1 \neq Z_2$, the Green's function is given by

$$G(Z,Z_o) = \frac{\left[n_1(Z_<) + R_1(Z_1)\,\frac{n_1(Z_1)n_2(Z_<)}{n_2(Z_1)}\right]\left[n_2(Z_>) + R_2(Z_2)\,\frac{n_1(Z_>)n_2(Z_2)}{n_1(Z_2)}\right]}{W(n_2,n_1)\left[1 - R_1(Z_1)R_2(Z_2)\,\frac{n_1(Z_1)n_2(Z_2)}{n_1(Z_2)n_2(Z_1)}\right]} \,,$$

(24)

where $Z_<$ and $Z_>$ denote the smaller or larger, respectively, of the variables Z and Z_o. $W(n_2,n_1)$ represents the Wronskian of n_2 and n_1. $n_1(Z)$ must be an outgoing wave for $Z \to -\infty$, and $n_2(Z)$ must be an outgoing wave for $Z \to +\infty$. The reflection coefficients are defined as

$$R_1(Z_1) = \frac{n_1^+(Z_1)}{n_1^-(Z_1)} \quad ; \quad R_2(Z_2) = \frac{n_2^-(Z_2)}{n_2^+(Z_2)} \quad , \tag{25}$$

where, by analytic continuation, the functions n_1 and n_2 are written as

$$\begin{aligned} n_1 &= n_1^+ + n_1^- \\ n_2 &= n_2^+ + n_2^- \quad . \end{aligned} \tag{26}$$

(That is, n_1 and n_2 are decomposed into upgoing and downgoing waves.)

If the region between Z_1 and Z_2 is taken as homogeneous and thin, then Eq. (24) can be simplified. In the case of the Epstein profile, Z_1 and Z_2 are taken in the region where the velocity variation is negligible.

When the reflection coefficient R_2 is referred to the level $Z = Z_1$, then the eigenvalue equation can be written as

$$R_1(Z_1)R_2(Z_1) = 1 \quad . \tag{27}$$

R_1 and R_2 are generally specified in terms of impedance conditions at the boundaries. However, in the present treatment R_1 and R_2 will not be functions of the boundary impedances.

Equation (24) will now be specialized to the Epstein profile with a rough surface. The function n_1 and n_2 for the Epstein profile are those already given by Eqs. (19) and (20). For the reflection coefficient R_1, Eq. (15) will be used, thus

$$R_1(Z_1) = \exp\left(-2(k_o \sigma \cos \theta)^2\right) \quad , \tag{28}$$

where

$$k_o \equiv k_{-\infty} \quad .$$

In order to obtain $R_2(Z_1)$, the analytic continuation for $n_2(Z)$ is used to give

$$R_2(Z_1) = \frac{\Gamma(-\lambda)\Gamma\left(\nu + \frac{\mu+\lambda}{2}\right)\Gamma\left(1 - \nu + \frac{\lambda+\mu}{2}\right)}{\Gamma(\lambda)\Gamma\left(\nu + \frac{\mu-\lambda}{2}\right)\Gamma\left(1 - \nu + \frac{\mu-\lambda}{2}\right)} \exp\left(2\lambda\zeta_1\right) \quad , \tag{29}$$

which is valid for $2|\zeta| \gg 1$. The Wronskian of n_2 and n_1 has already been given in reference 4.

When the period equation $1 - R_1R_2 = 0$ is solved for the complex eigenvalues ξ, then the residues yield the normal modes. Since the eigenvalues are complex, the modes are leaky (individually they do not satisfy the radiation condition). The following method is being used to calculate the complex eigenvalues.

First the period equation is written as

$$R_1\overline{R}_2 \exp\left(-2ik_oZ_1 \cos \theta_m\right) = e^{-2i\pi m} \quad ; \quad (m = 0, 1, 2, \ldots) \quad , \tag{30}$$

where

$$R_2 = \overline{R}_2 \exp\left(2\lambda\zeta_1\right) \quad ,$$

$$\lambda = -ik_o H \cos\theta \quad .$$

If the magnitudes of R_1 and $\overline{R}_2$ are each 1, then the angle θ is real and a simple solution is obtained with unattenuated upgoing and downgoing plane homogeneous waves. However, in Eq. (30) the magnitudes of R_1 and $\overline{R}_2$ are not each 1; therefore, Eq. (30) must be divided as follows:[5]

$$|R_1||\overline{R}_2| = \exp\left(-2k_o Z_1 \text{ Im} \cos\theta_m\right) \quad ,$$

$$\text{Im} \cos\theta_m = \frac{-\ln|R_1||R_2|}{2k_o Z_1} \quad , \tag{31}$$

$$\Phi_1 + \Phi_2 - 2k_o Z_1 \text{ Re} \cos\theta_m = +2\pi m \quad ,$$

$$\text{Re} \cos\theta_m = \frac{\Phi_1 + \Phi_2 - 2\pi m}{2k_o Z_1} \quad ,$$

where

$$R_1 = |R_1| \exp\left(i\Phi_1\right) \quad ,$$

$$\overline{R}_2 = |\overline{R}_2| \exp\left(i\Phi_2\right) \quad .$$

The complex eigenvalues $\xi_m = k_o \sin\theta_m$ are presently being computed by means of a complex gamma function routine which computes values for Re $\ln \Gamma(Z)$ and Im $\ln \Gamma(Z)$. This is fortunate, since

$$\text{Re } \ell n\, \Gamma(Z) = \ell n\, |\Gamma(Z)|$$

and (32)

$$\text{Im } \ell n\, \Gamma(Z) = \arg \Gamma(Z) \quad .$$

(Z in the gamma functions represents a complex number). These complex roots will then be used in calculating the residues. It is expected that this method will provide a way to incorporate the effects of a rough boundary on surface duct propagation.

APPENDIX

LIST OF REPORTS OBTAINED FOR SCATTERING DATA

1. Abramowitz, W., Crews, A., Erath, R., "Ocean Surface Reverberation: Surface Interface Scattering," Gruman Aircraft Engineering Corporation Report RE-252, Bethpage, New York (May 1966).

2. Adlington, R. H., "Acoustic-Reflection Losses at the Sea Surface Measured with Explosive Sources," J. Acoust. Soc. Amer. 35(11), 1834-1835 (1963).

3. Ament, W. S., "Forward and Back-Scattering from Certain Rough Surfaces," Electromagnetic Wave Theory Symposium, IRE Trans. on Antennas and Propagation, 369-373 (July 1956).

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6. Ball, E. C., Carlson, J. A., "Acoustic Backscatter from a Random Rough Water Interface," Thesis presented to the Naval Postgraduate School, Monterey, California (June 1967).

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9. Beard, C. I., Brooks, F. E., "Comparison of Predictions of Vector Model of Microwave Reflection from the Ocean with Experimental Results," Electrical Engineering Research Laboratory Report No. CF-2526, Electrical Engineering Research Laboratory, The University of Texas at Austin (June 1956).

10. Boles, W. D., Fung, A. K., Moore, R. K., "Bistatic Measurements of Acoustic Waves Scattered from a Statistically Rough Known Surface," J. Acoust. Soc. Amer. 45(4), 1040-1044 (1969).

11. Brown, J. R., Scrimger, J. A., Turner, R. C., "Reverberation from the Ocean Surface," Pacific Naval Laboratory Technical Memorandum No. 66-8, Pacific Naval Laboratory, Esquimalt, British Columbia (May 1966).

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13. ABSTRACT

In Section I a status report is given on the possible verification of ARL's forward scattering theory with data from the sea surface. The literature on forward and specular scattering has been thoroughly examined. No appropriate forward scatter data were found from the sea surface. Due to the lack of available sea surface data, a forward scatter experiment is presently being proposed at ARL's Lake Travis Test Station. A brief discussion and proposed experimental setup are described herein, along with some theoretical forward scatter predictions. In Section II the acoustic surface duct propagation problem for an irregular boundary is solved in terms of a contour integral. The roughness is incorporated into the boundary value problem by means of an effective reflection coefficient. Application is made to the surface duct transmission problem for a velocity-depth variation given by the Epstein profile. (U-FOUO)

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